ACOUSTIC EMISSION METHOD for DIAGNOSTICS and STRUCTURAL HEALTH MONITORING of CRITICAL STRUCTURES DURING OPERATION

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ABSTRACT *- Acoustic Emission (AE) Structural Health Monitoring (SHM) is an emerging field of modern engineering that deals with diagnosis and monitoring of structures during their operation. Increasing requirements for safety, development of tools and criteria for condition based maintenance (CBM), cost reduction are all driving development of AE SHM methods in different industries. The primary goal of AE SHM is detection, identification, assessment and monitoring of flaws or faults/conditions that affect or may affect in a future safety or performance of structures. AE SHM combines elements of AE testing, AE condition/process monitoring, statistical pattern recognition and physical modelling.*

In this work, the concept, definitions and principles of AE SHM are presented including fundamental assumptions regarding development of new AE SHM procedures, selection of equipment and methods of data acquisition and analysis, diagnosis, monitoring and prediction by AE SHM. Several important industrial examples are provided to demonstrate unique capabilities of AE SHM and their contribution to safety of critical structures. Particularly it is shown application of AE SHM for detection, assessment and long-term monitoring of flaws during normal operation of different industrial systems. It is also demonstrated how AE SHM is useful for identification of risk factors and causes of flaw origination and development thereby providing valuable information for predictive maintenance.

1. INTRODUCTION

Structural health monitoring in general and AE SHM in particular are emerging fields of engineering that deals with development and application of approaches for on-line assessment and monitoring of structures [1, 2, 3]. Safety and commercial needs are primary motivations behind AE SHM development.

1.1. SAFETY MOTIVATION

Analysis of failures in different industries over the word showed that proper design, selection of materials and construction do not necessary guaranty safety of structures in a long term. This is because structures can be subjected to extreme loads and harsh environmental conditions during their operational life. Material properties may degrade significantly over the time. Also, statistics of failures show that periodic non-destructive examinations of structures are not enough to prevent possible failures due to different reasons. Therefore, in order to reduce a risk of unexpected failure, it is necessary to develop methods capable of performing on-line, outage independent, global assessment and monitoring of structures.

1.2. COMMERCIAL MOTIVATION

Another driving force behind AE SHM is a commercial need to develop methods that can provide measurable, quantitative criteria for condition-based maintenance. CBM is a relatively new approach being adopted in different industries that defines maintenance schedule based on the condition of structure. In other words, maintenance is performed whenever and wherever is necessary, allowing cost effective operation, minimizing need in outages and reducing risk of failure.

1.3. ACOUSTIC EMISSION NON-DESTRUCTIVE AND STRUCTURAL HEALTH MONITORING METHOD

Acoustic emission is a phenomenon of sound and ultrasound (stress) waves radiation in materials subjected to stress during deformation and fracture processes. Acoustic Emission NDT method is based on detection, location and analysis of acoustic emission waves generated in structures subjected to stress (Figure 1). Detection of AE performed normally by special piezoelectric sensors, wideband or resonant in frequency range between 50 kHz to 2 MHz and positioned at distances of several meters one from another. Analysis of acoustic emission wave arrival rate, their amplitude, energy and frequency characteristics can provide valuable information about nature of the flaw, it position, propagation rate and severity.

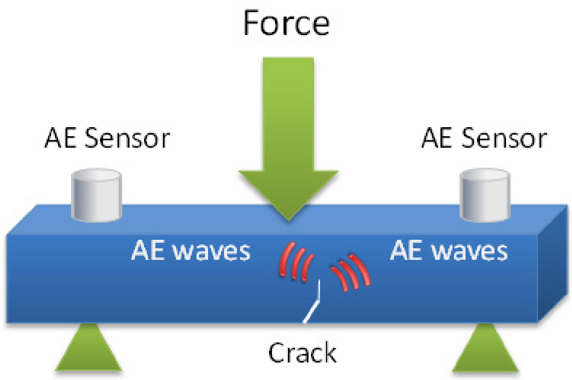


Figure 1. Acoustic emission waves generated due to crack development under stress in a solid material.

Acoustic emission method fits uniquely to the concept of structural health monitoring due to multiple phenomenological advantages. Particularly, it can be used for:

- *Diagnostics of overall structural integrity including detection, location, identification and assessment of flaws/faults during normal operation of a structure [4].*
- *Continuous or periodic monitoring.*
- *Identification of operation conditions that cause flaw/faults origination and development.*

Below, we elaborate fundamentals of structural health monitoring by the Acoustic Emission method, which include terminology and definitions, fundamental assumptions and standard process of AE SHM.

2. TERMINOLOGY AND DEFINITIONS

Structural health monitoring is relatively new engineering field and this probably explains the lack of standard and commonly excepted terminology. In order to ensure correct understanding of SHM terminology, the following list of terms and definitions was elaborated, where the terms flaw and fault were adopted form existing standards:

- *Structural health monitoring is a process of diagnosis and monitoring condition of structures normally performed during their operation.*
- *Diagnosis is a process of detection, identification and assessment of flaws, properties or conditions that affect or may affect in future safety/performance of a structure.*
- *Diagnostic AE is an acoustic emission methodology capable to achieve goals of diagnosis.*
- *Flaw – an imperfection or discontinuity that may be detectable by non-destructive testing and is not necessarily rejectable [5].*
- *Fault - an abnormal condition or defect at the component, equipment, or sub-system level which may lead to a failure [6].*
- *Monitoring - a process of follow-up over changes in the condition of a structure.*
- *Prediction – a process of estimation of possible future flaw/fault deterioration based on results of diagnostics, monitoring and/or numerical modelling.*

3. THE PROCESS OF STRUCTURAL HEALTH MONITORING

The process of structural health monitoring can be divided on the following typical stages:

- *AE SHM procedure development.*
- *Sensing.*
- *Diagnosis.*
- *Monitoring.*
- *Prediction.*

3.1. AE SHM PROCEDURE DEVELOPMENT

The first stage of procedure development is dedicated to collection of all necessary information regarding the structure, its design and materials, operational conditions, statistics of failures and etc. In addition, laboratory and/or full scale tests are conducted on structures with known flaws/faults at known stage of development in order to develop ability to detect, identify and assess specific flaws/faults in goal applications. Based on the collected information, an optimal instrumentation, methods of data acquisition and data analysis, and loading policies, and etc. are elaborated.

3.2. SENSING

Sensing is a process of data measurement. It involves measurement of AE as well as parametric data like pressure, temperature, strain and other according to the developed SHM procedure. There are several important aspects to address during the sensing stage. First, it is important check that data collected during data acquisition process is valid and can be satisfactory used for the purposes defined in the developed SHM procedure. If this is not a case, additional measurements with different setup or loading, operational and/or environmental conditions may be required. Second, during the sensing process, an express evaluation of a structure is normally performed to identify or rule out possible major conditions that may threaten the structure immediately or in a short term.

3.3. DIAGNOSIS

Diagnosis is one of the primary goals of SHM. It effectively distinguishes a typical AE NDE from AE SHM. The objectives of diagnosis process are not only to detect and locate flaws/faults as in typical NDE but also to identify and assess them. To achieve these objectives special development efforts are required including material research, numerical modelling, *and small or full scale samples tests. Diagnosis performed based on collected data using methods of statistical pattern recognition. Numerical modelling, analysis of stress conditions, history of the inspected structure, local application of different NDE methods, material investigations and other may be required to crystallize the most correct diagnostic picture of the condition of an examined structure.*

3.4. MONITORING

Monitoring performed to follow over condition of a structure over time. It is performed periodically or continuously depending on the particular application. For success of monitoring it is necessary to identify quantitative and/or qualitative AE characteristics that are changing with flaw/fault development. It is important to perform monitoring under normal operational and environmental conditions of a structure. If a change in stress/operational/environmental conditions occurs from any reason or a structure has been subjected to extreme influence and trauma, it may require change in a monitoring policy. Another important goal of monitoring is to identify conditions causing flaw/fault origination and development in the inspected structure. Examples of such conditions are fatigue, mechanical and thermal overstresses, and etc.

3.5. PREDICTION

The goals of prediction are to:

- *Identify the useful a remaining lifetime of structure.*
- *Define an appropriate re-inspection/monitoring policy based on diagnostic and monitoring results.*
- *Provide information necessary for CBM decisions.*

Prediction normally done based on diagnostic results, several monitoring and in conjunction with all information about the structure, its history and all know measurable or non-measurable risk factors.

4. FUNDAMENTAL ASSUMPTIONS OF AE STRUCTURAL HEALTH MONITORING

Structural health monitoring by the AE method as any other scientific concept is based on a set of fundamental assumptions that are normally self-evident and not necessary have to been scientifically proven. The role of assumptions is to define a systematic basis of a concept or theory. Based on the author experience in the fields of AE, fracture mechanics, material science, physics of solids, a set of fundamental assumptions of SHM by the AE method were elaborated [7]. It cannot be claimed at this moment that this set of assumptions is complete and thus further modifications and corrections could be required. Fundamental assumptions were divided to four groups: AE SHM procedure development, structure diagnosis and monitoring, data analysis, prediction and recommendations. Some examples of AE SHM axioms are provided below:

- *An optimal AE SHM procedure is one that ensures a maximum probability of flaw/fault detection while minimizing false negative findings.*
- *Development of new AE SHM applications is essentially based on a learning process. This includes collection and analysis of information about:*
  - *Structural design, history of operation, repairs and results of previous inspections.*
  - *Material properties.*
  - *Applied loads, operational and environmental conditions.*
  - *Typical flaws/faults that can develop in the inspected structure.*
  - *AE characteristics of flaws/faults to be detected, assessed and monitored.*
  - *Wave propagation characteristics in the material and geometry of the inspected structure including propagation modes, attenuation, dispersion, scattering and other characteristics.*
  - *AE instrumentation appropriate for the particular application.*
- *An optimal loading and/or environmental conditions for performing SHM are considered those under which flaws/faults naturally originate and develop in the inspected structure.*
- *Acoustic emission is flaw/fault-stage-material specific, i.e. different flaws and faults at different stages of their development in different materials have different AE characteristics.*
- *During flaw/fault assessment, a conservative approach should be taken in case of uncertain results. Flaws/faults that can be equally classified into two different groups by their severity level should be attributed to the group corresponding to more severe flaws/faults.*
- *Comparison of loading, operational and/or environmental conditions with AE activity or AE characteristics reflecting kinetic characteristics of flaws/faults development can be used to identify conditions causing flaw/fault origination, development, acceleration or arrest.*
- *Signal's features selected for data analysis should be a minimum set of statistically significant features necessary for the specific SHM application; filtered and normalized whenever is required so influence of background noise is minimized and data measured at different times and different locations is comparable.*
- *Features used in data analysis should have established relationship with physical phenomena being measured during AE SHM in order to insure correct diagnosis of the inspected structure.*

- *AE activity distinguishable from AE background noise should be considered as flaw/fault related activity unless different is proven.*
- *A non-developing flaw/fault cannot cause a failure unless there is a change in loading, operational and/or environmental conditions.*
- *Optimal re-inspection interval is such that a risk of unexpected failure is reduced to the minimum acceptable probability, defined for the specific application.*

5. ACOUSTIC EMISSION for DIAGNOSTICS and MONITORING of CRITICAL STRUCTURES DURING OPERATION

In the following examples an application of acoustic emission method for diagnostics and monitoring of critical structures is demonstrated.

5.1. EXAMINATION OF STEAM PIPING SYSTEMS IN OPERATION

Steam piping systems are considered critical structures in power, gas, oil, chemical and paper producing plants. History of catastrophic failures of steam piping triggered development of piping inspection programs that utilize a complex approach based on non-destructive examinations, material evaluation, stress analysis, remaining life time evaluation, periodic assessment and adjustment of hangers and supports and other. Today, non-destructive examinations of steam piping is performed in the most cases by various ultrasonic techniques, applied on several welds and normally in intervals of 3-7 years.

However, statistics of failures shows that flaws may initiate in unpredictable locations and develop to a failure in few months period which much shorter than intervals recommended for ultrasonic testing. Analysis of failures shows that detectability of creep, thermal fatigue and some other mechanisms by advanced ultrasonic testing methods is such that flaws are detected only on advanced stages.

Also, once flaws are detected it is practically impossible to evaluate their propagation rate or to monitor their development due to limitations of continuous plant operation and other reasons.

Due to significance of the problem and limitations of the existing approaches for investigation of piping integrity, development of AE method for investigation of steam piping became very important. It was necessary to develop a reliable AE methodology that will be capable to detect typical flaw mechanisms specific to this type of systems and have a good detectability under strong and variable background noise conditions produced by steam flow, operation of boiler and turbine.

So since late 1990's several AE methodologies for inspection of steam piping were developed. At the same time, Energy Power Research Institute, USA issued a guideline for inspection of seam welded steam piping by means of AE. In recent years, two new standards for inspection of steam piping were proposed to American Society for Testing and Materials.

One of these standards [8] is proposed by the author of this article. It describes purposes, process and main consideration of acoustic emission examination of steam piping during their normal operation and particularly describes that:

- *The purpose of AE examination is to identify conditions that affect or may affect in the future the structural integrity of the steam piping.*
- *AE examination can be used for detection, location, identification and assessment of sources due to flaw accumulation and development in steam piping during operation.*
- *AE examination can be used for identification of operational conditions causing or contributing to flaw origination and development and for identification of piping issues related to thermal shock, valve leaks, valves malfunctioning, steam fluctuations and turbulence, improper performance of hanger and support systems, impacts, friction due to piping interference, and events of water hammer, thereby providing valuable information for piping maintenance.*

Practical installation of AE system includes installation of AE sensors at average 3-5 meters distance one from another. Due to a high temperature of the pipe surface, sensors are mounted on special waveguides that are spot welded on the piping surface. Modern multichannel AE systems allow monitoring several hundred of meters of piping simultaneously while performing online filtration, AE source location and assessment.

AE monitoring is performed normally for several days while under different operational conditions typical for the examined piping. The collected data is then goes through several typical steps of data analysis:

- *Location – different methods are applied for evaluation of AE source location. Commonly applied methods are time-difference linear location for burst AE signals, zone location, and energy attenuation based linear location for continuous and burst AE signals. In the case of energy attenuation based location, noise normalization is performed to reduce location error due to difference of background noise conditions at different sensors.*

- *Location clustering is be performed to identify AE source characteristics including likely AE origin, number of emissions vs. time vs. physical location, etc. Special attention is made on AE sources distributed along long sections of seam welds of seam welded piping due to the fact that developing flaws distributed along seam weld may cause catastrophic failure. AE activity locations is compared with position of circumferential welds, welded piping accessories, hangers and supports, findings of visual survey.*
- *Flaw-indication identification and assessment. When proper methods of data analysis and criteria are developed, AE data is used for flaw-indication identification and assessment. Acoustic emission is flaw/fault-stage-material specific, i.e. different flaws and faults at different stages of their development in different materials have different AE characteristics. Therefore, flaw/fault identification (typification) and assessment is possible when unique AE characteristics characterizing different flaws/faults indications at different stages of their development in the specific piping material can be identified, effectively distinguished and compared with similar characteristics obtained in similar applications and/or in laboratory tests with known flaws/faults at known stages. Features used in data analysis should have an established relationship with physical phenomena being measured during AE examination in order insure correct assessment of the examined piping. Signal parameters used for assessment of indications should be a minimum set of statistically significant features; filtered and normalized whenever is required so influence of background noise is minimized and data measured at different times and different locations is comparable.*
- *AE location vs. time vs. operational conditions (temperature, pressure, etc.) analysis. Comparison of loading and operational conditions with AE activity and/or AE data parameters can be used to identify conditions causing flaw/fault accumulation, development, acceleration or arrest.*
- *Hanger and support malfunctioning analysis. It is important to identify impacts and friction in welded connections of hangers and supports. These events present risk factors even if there is no indications of flaw related activity. Normally, in properly adjusted hanger system, there should be no hanger impact or friction activity.*

In case of significant findings, other NDE methods and/or methods of metallurgical investigation might be recommended for further characterization of flaw indications and/or for decision making regarding possible repair.

The results of hundreds of inspections performed by different AE vendors and confirmation tests showed that:

- *AE method is capable to detect practically all main failure mechanisms typical for steam piping systems.*
- *There were several cases when AE examination warned about impending failure.*
- *AE examinations demonstrated effective detection of leaks, hydraulic and steam shocks, hangers and valves malfunction.*

5.2. DIAGNOSTICS AND MONITORING OF FIBER REINFORCED PLASTICS PRESSURE VESSELS DURING OPERATION IN A DESALINATION PLANT.

There is a significant shortage of fresh water in number of regions in the World. This forces local governments to invest into water purification technologies, construction of water purification utilities and particularly water desalinations plants.

Reverse-osmosis is one of the popular technologies used today for a large scale water desalination measured by millions of cubic meters/year. Reverse-osmosis process removes salts and impurities from sea water by pushing it through membrane filters under pressure. Plants that use reverse osmosis process produce high quality water in large volumes while requiring relatively low operational costs and reduced energy consumption.

One of the main components of the desalination reverse osmosis process are fiber reinforced plastics (FRP) pressure vessels that are used as pressure housing for reverse osmosis filters. Typically there are hundreds of such pressure vessels in each facility connected serially into trains. FRP vessels are several meters long and operate under relatively high pressure.

Failure of FRP vessels during operation can occur in different ways. One of the common failure scenarios is leak before burst which results in two types of leaks: high pressure "spraying" leak or small "bleeding" leak. The first type of leak is easy to identify but the second one can remain undetected for a long time. Normally, the first type of leak occurs when there is a direct passage of water through the vessel wall while the second type of leak occurs when water goes in a complex way along delaminations developed in the composite vessel. The first type of leak may pose a safety hazard if occurs unexpectedly and close to plant personnel.

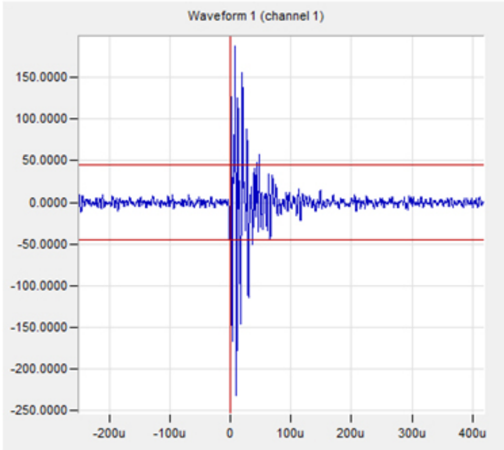
Another type of failures can lead to catastrophic circumstances. There are recorded cases of catastrophic rupture of vessels before a visible leak could be detected. Such violent failure may result in large parts of vessels *flying and endangering people around. Failures of vessels also interrupt operation and if occur often can lead to significant economic losses.*

Acoustic emission technology is an effective tool for on-line diagnostics and monitoring of FRP vessels used in reverse-osmosis process because:

1. *Easy to install system with few sensors only can be used for inspection of entire vessel under normal operation loads (Figure 2, 3).*
2. *AE detects effectively matrix cracking, delamination growth and fiber breakage in FRP vessels and can identify flawed vessels long before they fail (Figure 4).*
3. *Using special AE analysis methods it is possible not only to detect flaw indications but to distinguish between them accurately (Figure 4) and assess their significance to the structural integrity of the vessel.*
4. *In addition to flaw related activity, AE technology is used to detect leaks those difficult to identify by other means.*
5. *Once defective vessels are identified, they can be effectively monitored to the moment when replacement is required.*

Figure 2. Installation of AE system on FRP vessels.

Figure 3. AE monitoring of several FRP vessels.



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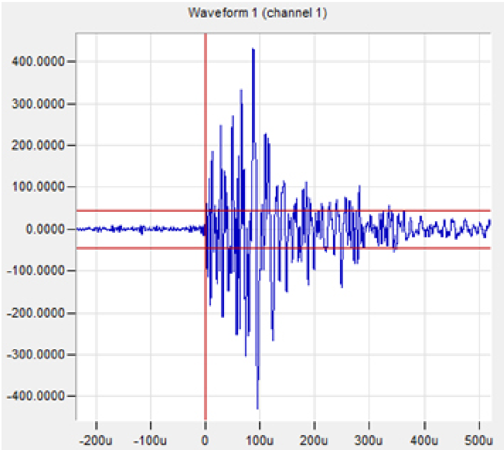

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Figure 4. Typical signal of matrix cracking (a) and delamination development (b) in the examined FRP vessels.

6. CONCLUSIONS

Acoustic Emission is a unique non-destructive test method that allows on-line diagnostics and monitoring of critical structures. Results of practical application of the method demonstrate reliable for practical needs detectability and assessment of dangerous flaws of different nature. Due to its application under normal stress and operational conditions, AE method can be used for identification of risk factors causing flaw initiation and development as hydraulic shocks, dynamic overstresses and many others.

7. REFERENCES

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